Spin effects in $pd \to {}^3\mathrm{He}X$ reactions

L. A. Kondratyuk
Institute of Theoretical and Experimental Physics, 117259 Moscow, Russia

Yu. N. Uzikov[a)]
Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, 141980 Dubna, Moscow District, Russia

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It is shown that a two-step model of the reaction $pd \to {}^3\mathrm{He}X$ ($X = \eta$, η', ω, ϕ), involving the subprocesses $pp \to d\pi^+$ and $\pi^+ n \to Xp$, can account for the form of the energy dependence of experimental cross sections above the thresholds under the assumption that the singlet part of the $pp \to d\pi^+$ amplitude dominates. The spin–spin asymmetry for the reaction $dp \to {}^3\mathrm{He}X$ has been found to be ~ -1 in the forward–backward approximation. © *1996 American Institute of Physics.* [S0021-3640(96)00101-6]

Reactions $pd \to {}^3\mathrm{He}X$, where X means a meson heavier than the pion, are of great interest for several reasons. First, high momentum transfer ($\sim$1 GeV/c) to the nucleons takes place in these processes. Second, unexpectedly strong energy dependence of η meson production was observed near the threshold.[1] In this respect the possible existence of quasi-bound states in the $\eta - {}^3\mathrm{He}$ system is discussed in the literature.[2,3] Third, production of the η, η', ϕ mesons, whose wave functions contain valence strange quarks, raises a question concerning the strangeness of the nucleon and the mechanism of Okubo–Zweig–Iizuka rule violation.[4] An experimental investigation of the reaction $dp \to {}^3\mathrm{He}\phi$ at Dubna has been proposed[5] to check the hypothesis that the nucleon possesses a polarized strangeness content.[4] Thus the investigation of conventional (nonexotic) mechanisms of the reaction in question is of great importance.

The important role of the intermediate pion beam in the reaction $pd \to {}^3\mathrm{He}\eta$ was demonstrated in Ref. 6. As was mentioned for the first time in Ref. 7, at the threshold of the reaction $pd \to {}^3\mathrm{He}\eta$ a two-step mechanism, including two subprocesses $pp \to d\pi^+$ and $\pi^+ n \to \eta p$, is favored. The advantage of this mechanism is that at the threshold of this reaction and at zero momenta of Fermi motion in the deuteron and ^{3}He nucleus, the amplitudes of these subprocesses are practically on the energy shells. It is easy to check that this peculiarity (the so-called velocity matching or kinematic miracle) takes place above the threshold too, if the c.m.s. angle $\theta_{c.m.}$ of the η meson production in respect to the proton beam is $\theta_{c.m.} \sim 90°$. For the ω, η', and ϕ mesons velocity matching takes place above the corresponding thresholds only at $\theta_{c.m.} \sim 50° - 90°$, depending on the meson mass and the energy of the incident proton. The two-step model of the $pd \to {}^3\mathrm{He}\eta$ reaction was developed in Refs. 3 and 8. Recently it was found[9] that the two-step model can describe the form of the threshold cross sections of $pd \to {}^3\mathrm{He}X$ reactions as a function of the mass of produced meson $X = \eta, \omega, \eta', \phi$. The absolute value was underestimated by an overall normalization factor of about 2.4. However, the above-threshold behavior of the cross sections was not investigated in spite of available experimental data,[10] and the spin observables are not discussed.

In this work the two-step model[3] is extended for the production of η,ω,η' and ϕ mesons above the thresholds (at final c.m.s. momenta p^* of about several hundred MeV/c). From the description of the energy dependence of the cross section above threshold we conclude that the singlet amplitude in the spin structure of process $pp\to d\pi^+$ dominates. On this basis we predict the spin–spin correlation for the reaction $dp\to {}^3\mathrm{He}X$ at the energy region of the proposed Dubna experiment.[5]

In the general case the cross section of the reaction $dp\to {}^3\mathrm{He}X$ with polarized colliding particles is too cumbersome. Let us consider at first the spin-averaged cross section. In the two-step model it can be represented in the following formally separable form

$$\frac{d\sigma}{d\Omega}=R_S K|\mathscr{F}(P_0,E_0)|^2\,\frac{d\sigma}{d\Omega}\,(pp\to d\pi^+)\,\frac{d\sigma}{d\Omega}\,(\pi^+n\to Xp), \tag{1}$$

where K is the kinematic factor defined according to Eq. (21) in Ref. 3 for the differential cross section, derived in a spinless approximation. (Indeed, the factor K from Ref. 3 is multiplied here by factor $(9/8)^2$ in order to obtain the correct normalization condition for the vertex function $d+p\to {}^3\mathrm{He})$. The formfactor $\mathscr{F}(P_0,E_0)$ in Eq. (5) can be expressed through the S and D components of the nuclear wave function φ_l by the following integrals:

$$\mathscr{F}_{Lll'}(P_0,E_0)=\frac{1}{4\pi}\int_0^\infty j_L(P_0r)\exp(iE_0r)\varphi_l^\tau(r)\varphi_{l'}^d(r)r\,dr; \tag{2}$$

the normalization integral $\int_0^\infty[\varphi_0^2(r)+\varphi_2^2(r)]r^2dr$ equals 1 for the deuteron and $S_{pd}^\tau=1.5$ (Ref. 11) for the ^{3}He. The variables E_0 and P_0 are defined in Ref. 3. In comparison with Ref. 8 we do not use the linear approximation in Fermi momenta of the nucleons but instead take this dependence into account exactly. In the S-wave approximation we have $\mathscr{F}(P_0,E_0)=F_{000}$.

The additional factor R_S in Eq. (5), which is absent in Ref. 3, takes into account spins and generally depends on mechanism of the reaction because of the complicated spin structure of the amplitudes $A_1(pp\to d\pi^+)$ and $A_2(\pi^+n\to Xp)$. The analysis is simpler at the angles $\theta_{c.m.}=0°$ and 180°. In this case the production of a pseudoscalar meson $\pi^+n\to Xp$ in the forward–backward direction is described by only one invariant amplitude. The processes $pp\to d\pi^+$ and $\pi^+n\to\omega(\phi)p$ are determined by two forward–backward invariant amplitudes a_i and b_i according to the following expressions[12]

$$\hat{A}_1(pp\to d\pi^+)=a_1\mathbf{e}\cdot\mathbf{n}+ib_1\vec{\sigma}\cdot[\mathbf{e}\times\mathbf{n}], \tag{3}$$

$$\hat{A}_2(\pi^+n\to p\omega)=a_2\mathbf{e}\cdot\sigma+b_2(\vec{\sigma}\cdot\mathbf{n})(\mathbf{e}\cdot\mathbf{n}), \tag{4}$$

where $\mathbf{n}$ is the unit vector along the incident proton beam, $\mathbf{e}$ is the polarization vector of the spin-1 particle (d,ω,ϕ), σ denotes the Pauli matrix. According to our numerical calculations, the contribution of the D component of the nuclear wave functions to the square modulus of the form factor $|\mathscr{F}(P_0,E_0)|^2$ is less than $\sim$10% for the deuteron and less than $\sim$1% for ^{3}He. Using the S-wave approximation for the nuclear wave functions and taking into account Eqs. (3) and (4) we have found the following expressions for the spin factor R_S of the spin-averaged cross section in the two-step model

$$R_0=\frac{1}{3}\left(\frac{1}{2}|a_1|^2+\frac{2}{3}|b_1|^2-\frac{2}{3}\,\mathrm{Re}(a_1b_1^*)\right)\left[\frac{1}{2}|a_1|^2+|b_1|^2\right]^{-1} \tag{5}$$

$-$ for the pseudoscalar mesons and

$$R_1=\frac{1}{3}\left[\frac{1}{2}|a_1|^2(3|a_2|^3+\gamma)+\frac{2}{3}(|a_2|^2+\gamma)\mathrm{Re}(a_1b_1^*)+\frac{2}{3}|b_1|^2(5|a_2|^2+\gamma)\right]$$
$$\times\left[\frac{1}{2}(|a_1|^2+2|b_1|^2)(3|a_2|^2+\gamma)\right]^{-1} \tag{6}$$

for the vector mesons, where $\gamma=|b_2|^2+2\,\mathrm{Re}(a_2^*b_2)$. It follows from Ref. 12 that $|b_1|/|a_1|\sim0.1$ at the threshold of η meson production $T_p\sim0.9$ GeV, and one can therefore put $R_0=1/3$ (Refs. 8 and 9). Unfortunately, no experimental data on the spin structure of the $pp\rightarrow d\pi^+$ and $\pi^+n\rightarrow\omega(\phi)p$ amplitudes at energies $T_p\geqslant1400$ MeV are available. Thus, the exact absolute magnitude of the spin factors and the cross sections is rather questionable. We have found numerically from Eqs. (5) and (6) that the values R_0 and R_1 vary in the range from 1/9 to 4/9 when the complex amplitudes a_i and b_i vary arbitrarily. A remarkable peculiarity of the condition $|a_1|\gg|b_1|$ is that in this case the spin factor R_1 for vector mesons does not depend on the behavior of amplitudes a_2 and b_2 and in accordance with Eq. (6) it equals $R_1=1/3$. This value is very close to the maximal one $R_S^{max}=4/9$. It will be shown below that assumption $|a_1|\gg|b_1|$, which provides the condition $R_0=R_1=\frac{1}{3}=$const, is compatible with the main features of the observed cross sections for η, ω, and η' meson production. The numerical calculations are presented below at $R_0=R_1=\frac{1}{3}$.

The numerical calculations are performed using nuclear wave functions and parametrization for the $pp\rightarrow d\pi^+$ reaction as in Ref. 3. The experimental data on the total cross section of the reactions $\pi^+n\rightarrow p\eta(\eta',\omega,\phi)$ are taken from Refs. 13 and 14 and the isotropic behavior of the differential cross section is assumed here. The numerical results are obtained in the S-wave approximation for the spin-averaged cross sections and with the D component of the deuteron taken into account for the spin correlations. The results of calculations of the differential cross sections are presented in Figs. 1 and 2 in comparison with the experimental data.

Numerical calculations show that under the assumption $|a_1|\gg|b_1|$ the two-step model:

(i) describes the shape of the energy dependence of the observed cross sections for η,η',ω meson production (see Figs. 1 and 2);

(ii) predicts the ratio of the square moduli of the threshold amplitudes as $R(\phi/\omega)=|f(pd\rightarrow{}^3\mathrm{He}\phi)|^2/|f(pd\rightarrow{}^3\mathrm{He}\omega)|^2=0.52$, in agreement with the experimental value $R^{exp}=0.07\pm0.02$;

(iii) explains the absolute value of the cross section of the reaction $pd\rightarrow{}^3\mathrm{He}\omega$ at $T_p=3$ GeV, $\theta_{c.m.}=60°$ (this kinematical region corresponds to the matching condition);

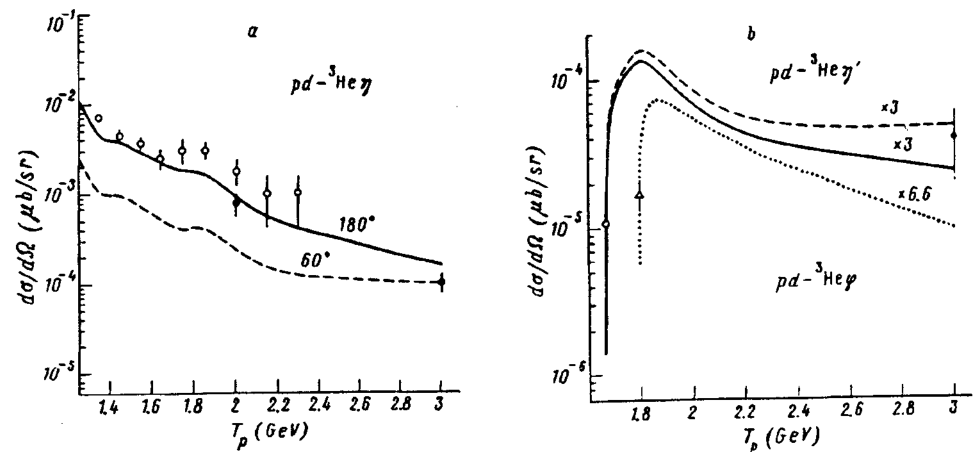

FIG. 1. Differential cross sections of the $pd \to {}^3\mathrm{He}\,\eta(\omega,\ \eta',\ \phi)$ reactions as a function of the laboratory kinetic energy of proton T_p. The curves show the results of calculations at $R_S = \frac{1}{3}$ for different angles $\theta_{c.m.}$ multiplied by the appropriate normalization factor N. a) $pd \to {}^3\mathrm{He}\,\eta$: 180° (solid curve, $N=3$), 60° (dashed curve, $N=3$); the circles are experimental data: ○—$\theta_{c.m.}=180°$, Ref. 1, ●—$\theta_{c.m.}=60°$, Ref. 15; b) $pd \to {}^3\mathrm{He}\,\eta'$ at $\theta_{c.m.}=180°$ (solid, $N=3$) and $\theta_{c.m.}=60°$ (dashed, $N=3$); the circles are experimental data for the η' production: ○—$\theta_{c.m.}=180°$, Ref. 16; ●—$\theta_{c.m.}=60°$, Ref. 15; the dotted curve shows the results of calculation for the $pd \to {}^3\mathrm{He}\,\phi$ reaction at $\theta_{c.m.}=180°$ normalized by factor $N=6.6$ to the experimental point (△) from Ref. 16.

(iv) is consistent, within the experimental errors, with the experimental data[15] on the absolute value of the cross section for η' production at $T_p=3$ GeV, $\theta_{c.m.}=60°$ (this kinematical region corresponds to the matching condition).

Therefore the assumption $|a_1| \gg |b_1|$ seems to be reasonable enough. It allows us to make a definite prediction for the spin–spin correlations in the reaction $pd \to {}^3\mathrm{He}X$ with polarized deuteron and proton. Assuming that the polarization vectors of the proton $\mathbf{P}_p$ and deuteron $\mathbf{P}_d$ are perpendicular to the incident beam and that the polarization tensor of the deuteron is zero, we obtain the following expression for the spin–spin asymmetry:

$$\Sigma_X = \frac{d\sigma(\uparrow\uparrow) - d\sigma(\uparrow\downarrow)}{d\sigma(\uparrow\uparrow) + d\sigma(\uparrow\downarrow)} = -\frac{|\mathscr{F}_{000}|^2 - |\mathscr{F}_{202}|^2 - \frac{1}{\sqrt{2}}\,\mathrm{Re}(\mathscr{F}_{000}\mathscr{F}^*_{202})}{|\mathscr{F}_{000}|^2 + |\mathscr{F}_{202}|^2}, \tag{7}$$

where $d\sigma(\uparrow\uparrow)$ and $d\sigma(\uparrow\downarrow)$ are the cross sections in the cases of parallel and antiparallel orientation of the polarization vectors of the proton and deuteron. We have found numerically from Eq. (7) that $\Sigma_\phi = -0.95$ near the threshold and goes very rapidly to -1 above the threshold. A very similar result is obtained for the ω meson: $\Sigma_\omega = -0.92$. Neglecting the D component of the deuteron wave function, we obtain the same result for vector and pseudoscalar mesons: $\Sigma_{\phi,\omega} = \Sigma_{\eta,\eta'} = -1$. It should be noted that a positive value for Σ_ϕ is expected on the basis of the $s\bar{s}$ hypothesis.[4]

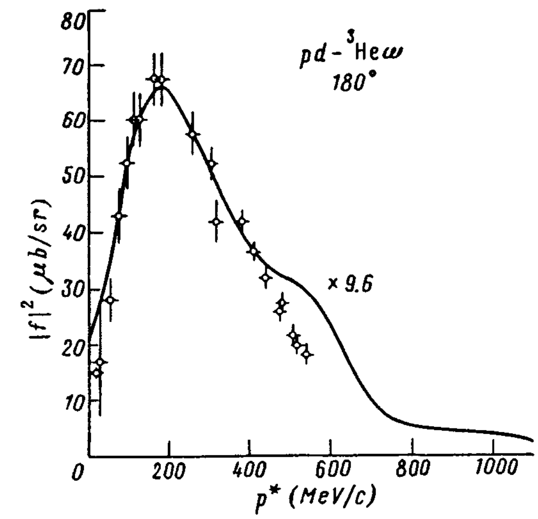

FIG. 2. The square modulus of the amplitude of the $pd\to{}^3\mathrm{He}\omega$ reaction as a function of the c.m.s. momentum p^* of the ω meson. The curve is the result of a calculation for $R_1=\frac{1}{3}$ multiplied by a factor $N=9.6$; the circles (○) are experimental data.[10]

In conclusion, the absolute value of the cross section for vector mesons is substantially smaller than the experimental value. At the threshold ($p^*\sim 20$ MeV/c) the normalization factor N for ω- is 5.9 and for ϕ-meson is 6.6. To describe the absolute magnitude of the cross section in the range of 100 MeV/$c \leqslant p^* \leqslant 400$ MeV/c one needs a normalization factor $N=9.6$, which is substantially larger than the value 2.4 found in Ref. 9 at the threshold. The fairly satisfactory description of the form of the square modulus of the amplitude $|f(pd\to{}^3\mathrm{He}\omega)|^2$ together with a shortfall of the absolute value by an order of magnitude is the main puzzle of this model. The experiments with polarized particles[5] can give new, very important information about the mechanism in question.

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[a)]e-mail address: uzikov@nusun.jinr.dubna.su

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